

## 3.0 Materials in the Current Air Force

### 3.1 Introduction

It is often said that those who fail to heed the lessons of history are condemned to repeat them, and this is no more true than in politics and technology. It therefore behooves us to examine the role of materials in the past and current Air Force, with the goal of identifying the roles played by advanced materials in the development of Air Force systems. In particular, we seek to identify reasons why certain materials were introduced into aircraft systems, to identify the factors that controlled their rate of introduction, and to ascertain the impact of these materials on aircraft operation from an historical perspective. For example, we often hear that a new material was introduced to improve performance, but improved performance means different things to different people. Thus, we all accept that new materials have allowed for greater airspeeds (e.g., titanium in the SR-71), but have they improved payload?

In this chapter, we explore these issues from an historical perspective by examining the performance characteristics of a large number of military and civil aircraft extending from World War I to the present day. Much of this analysis has been made possible by the generosity of Richard N. Hadcock, RNH Associates, Inc., who kindly allowed us to use statistical data on various aircraft systems prior to their publication in book form.

### 3.2 Structural Materials

The first aircraft to fly, the Wright Flyer in 1903, was fabricated largely from composite materials. The choice of this material was dictated by various factors, including weight, strength, cost, and, of course, availability. Over the two decades that followed this historic event, wood and fabric reigned supreme with only a few excursions by designers into the use of metals for systems other than engines, bracing, controls, and landing gear (Table 3.1). From an historical

*Table 3.1 Airframe Structure Definitions: 1915-1940*

Construction Type	Elements
Composite Structure	<ul style="list-style-type: none"><li>• Wood, steel, or aluminum framing</li><li>• Steel bracing wires (internal and external)</li><li>• Fabric or aluminum non-stressed skins</li></ul>
Stressed Skin Construction	<ul style="list-style-type: none"><li>• Wood, metal or composite load-carrying skins supported by wood, metal or composite internal structure (spars, ribs, bulkheads, or frames)</li></ul>
Transition from composite to alclad stressed skin construction accomplished by major companies	<ul style="list-style-type: none"><li>• Germany 1918-1930</li><li>• United States 1930-1936</li><li>• France 1932-1938</li><li>• United Kingdom 1930-1939</li><li>• Japan 1934-1938</li><li>• USSR 1922-1944</li></ul>

perspective, it is important to note that wood is a biological composite material containing cellulosic fibers embedded in a natural resin. Likewise, fabric, principally linen as used in the early days of aviation, is a refined material in which natural fibers have been woven into a cloth. After being stretched over frames, the cloth is impregnated with resin to make the composite taut and impervious to air and water. Interestingly, this process has a lot in common with modern day composite manufacturing, but, of course, today the fibers and resins are high-performance synthetic materials. Nevertheless, the comparison is striking, and it illustrates that the real change over the past 90 years has been in the materials.

As the performance of aircraft improved, new materials were required to support greater aerodynamic stresses. These materials were high-strength steels and aluminum alloys. However, penetration of these materials into the aircraft industry was not rapid (Table 3.2). Indeed, as late as the Second World War, some high-performance military aircraft still made extensive use

*Table 3.2 Aluminum Alloys in Airframes: 1912-1995*

Year	Alloy	UTS (ksi)	Aircraft	Applications	Remarks
1912	1100 Pure Hard	24	Reissner	Wing, canard	Corrugated Al skins
1915-1919	Al Cu Mn "Duralumin" (17-S)	50-55	Germany: Dornier Junkers France: Bréguet Britain: Short	Wings, fuselages, tail units, struts	Alloy invented by Alfred Wilm, 1908 Some corrosion and cracking problems
1920	Alcoa 17S and 14S products	45-55	U.S.: Stout 1923	Complete airframes: corrugated skins	"Alclad" has excellent corrosion resistance
1926	Alcoa "Alclad" Al clad 17S sheet	50	Ford Trimotor 1926	Formed sheet or extrusions, substructure	Ford/Stout construction infringement of Junkers patents No European sales permitted
1931-1955	2024 Al-Cu - bare - clad sheet - forgings  Equivalent European and Japanese alloys	64 56	U.S.: Northrop Douglas Martin Boeing  Foreign: all major manufacturers	Complete airframes: stressed-skin, semi- monocoque, and integral structure	Standard material for WWII aircraft
1940-1995	7075-T6 Al-Zn -bare -clad sheet -forgings  Equivalent European and Japanese alloys	80	World-wide use of 7075 and foreign equivalents	Complete airframes: compression- dominated stressed skin, semi- monocoque, and integral structure. Used in combination with 2024	Japan: Used in "Zero" spars in 1940 U.S.: Used for reinforcement of B-29 "Enola Gay" in 1945 Standard military aircraft material, 1946-1990
1971-1995	7075-T76 Al-Zn  As above	75	Preferred to -T6	Used in place of 7075-T6	Improved stress corrosion resistance to 7075-T6
Note: Aluminum construction was finally accepted for airframes by most aeronautical engineers and aircraft users about 1935. This was 20 years after the first use of "Duralumin" in 1915 by Prof. Claude Dornier for the Rs.I flying boat lower fuselage covers and struts.					

of wood (e.g., the deHavilland Mosquito, troop-carrying gliders, and later the Spruce Goose of Howard Hughes' fame). The first use of structural metals in the aircraft industry had to await a crucial materials development: a corrosion-resistant aluminum alloy in the form of Duralium. Metals then became extensively used in high-performance military aircraft, but their penetration was not complete until the end of WW II. Subsequent alloy development produced materials of higher strength and better fatigue resistance that allowed aircraft to fly faster and higher and carry heavier loads. Surprisingly, when one considers the multitude of possible alloy systems, only a handful of aluminum alloys penetrated the industry, including "pure" aluminum (Alloy 1100), Duralium, Alcoa 17S, Alclad (Al clad 17S sheet), Alloy 2024, Alloy 7075-T6, and Alloy 7075-T76, which exhibits improved resistance to stress corrosion cracking compared to the T6 heat of the same alloy. Part of the explanation for the slow transition of new materials into aircraft prior to WW II is that the airplane industry is very conservative, particularly when it comes to the introduction of new materials into man-rated systems. Thus, designers insist on having extensive property databases before specifying new materials in airframes and engines. This conservatism was largely justified, as evidenced by the historical lack of involvement of new materials in aircraft accidents, but it did result in a lack of flexibility in developing new airplane systems.

It is interesting to note that the problems experienced in the introduction of metals into aircraft were well recognized at the time. For example, in 1935 it was noted that:

"The fundamental reason for the structural difficulties encountered in metal airplane structures was the lack of suitable alloys, technique of heat treatment, fabrication inexperience, and cost"

and

"The gradual transition to the metal structure has not been of rapid rate. The period of transition has been forestalled by the scarcity of sound engineering data and the method for economical production"<sup>2</sup>

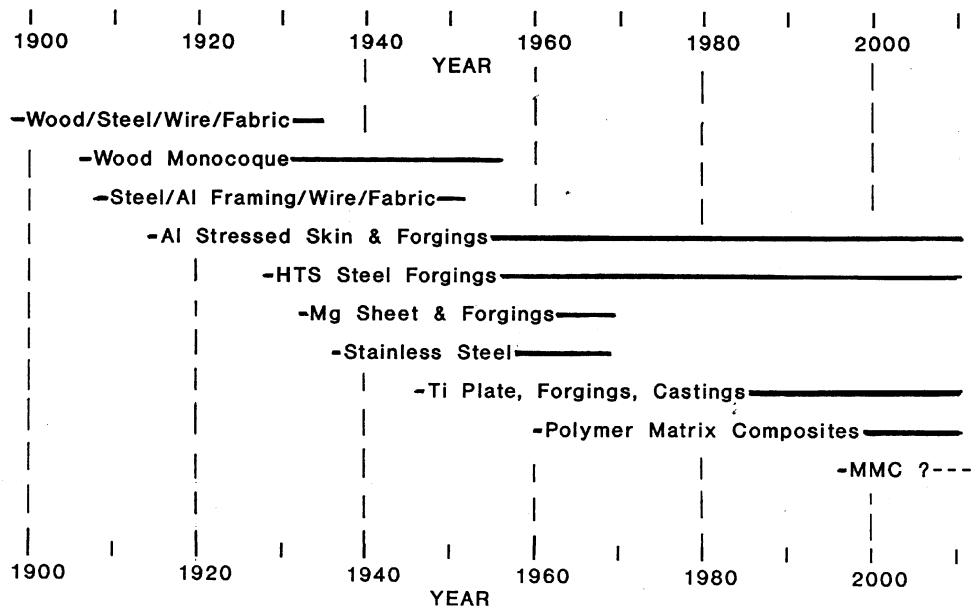
This statement could easily be made in 1995 with respect to current attempts to introduce advanced composite materials into aerospace systems. We note that this problem is not unique to the aerospace industry because identical difficulties arise in any industry where reliability is of paramount importance. For example, efforts to introduce aluminum into the automobile industry as a replacement for steel have been met with strong opposition, even though the savings to the consumer in terms of improved mileage has been well documented. Likewise, efforts to introduce composites into automobiles, even into expensive ones, have met with little success.

So far, we have described only two of many materials that appear in aerospace systems. A partial list of aerospace materials, together with their times of introduction, is given in Figure 3.1. One notes that over the past 50 years, only two new major structural materials, titanium and polymer matrix composites, have been introduced. Despite their high cost, both were introduced, because they allowed quantum leaps in performance.

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2. Willis L. Nye, *Metal Aircraft Design & Construction*, Aviation Press, 1935.

# AIRCRAFT MATERIALS & STRUCTURES



RNH Associates, 1995.

Figure 3.1 Aircraft Materials and Structures

Historically, materials have been introduced into military aerospace systems because they offer the designer improved performance. One performance factor that has increased markedly since the days of wood and fabric is the specific tensile strength, as shown in Figure 3.2. One sees the superior tensile strength of graphite fiber-reinforced plastic, even when compared with titanium, and this explains the great current interest in this material. However, strength degrades with increasing temperature, so that a material that provides satisfactory performance at ambient temperature may not do so at high Mach numbers. This is illustrated by the data shown in Figure 3.3, in which the specific tensile yield strengths of a variety of materials are plotted as a function of temperature. These materials include alloys Ti-6-4, Weldalite 049, Al 2618, a polymer matrix composite Celion 3000/PMR-15, and three metal matrix composites 2124/SiC/15w, 8009/SiC/11p, and 2124/TiB2/15p(XD). Note that the quantity that is plotted on the ordinate is the specific tensile yield strength, which is the yield strength divided by the density. Thus, low-density materials may have excellent specific tensile yield strengths, even though their total yield strengths are low. The superior performance of Weldalite 049, which is an aluminum/lithium alloy, at low temperatures is evident, and it is this property that has attracted designer attention to aluminum/lithium alloys in general over the past decade. At higher temperatures, particularly at temperatures above the range corresponding to Mach 2.4 operation, this alloy fares poorly and is no better than Al 2618 and titanium diboride metal matrix composite.

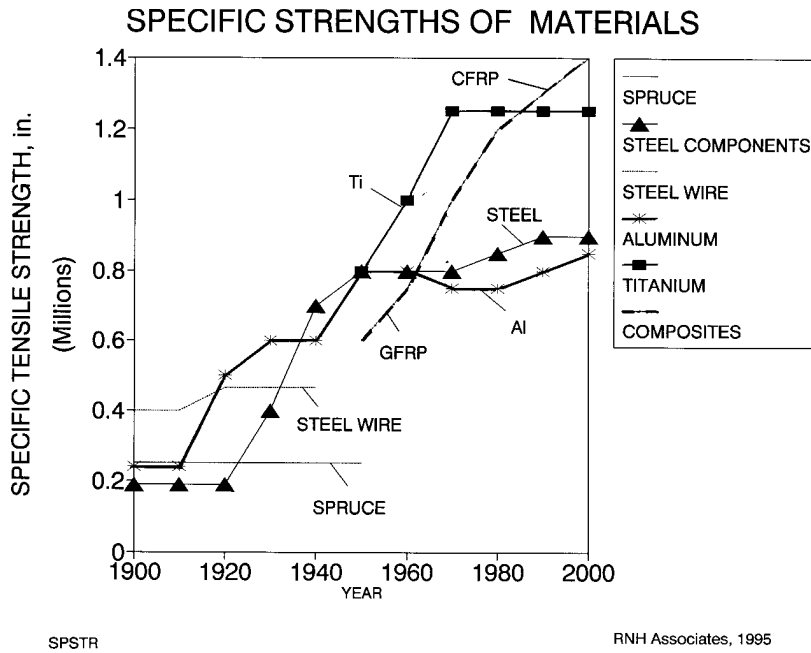


Figure 3.2 Specific Strengths of Materials

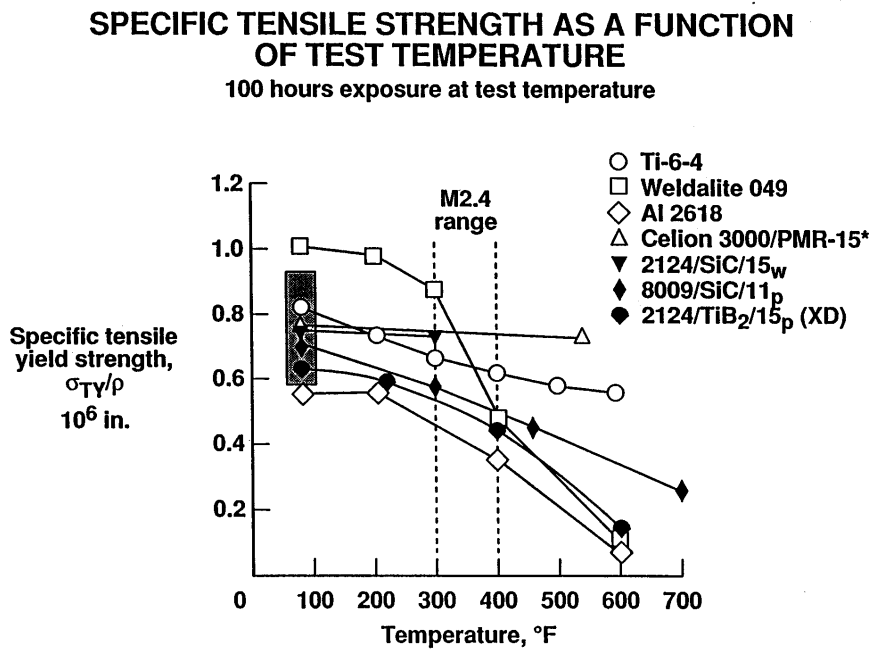
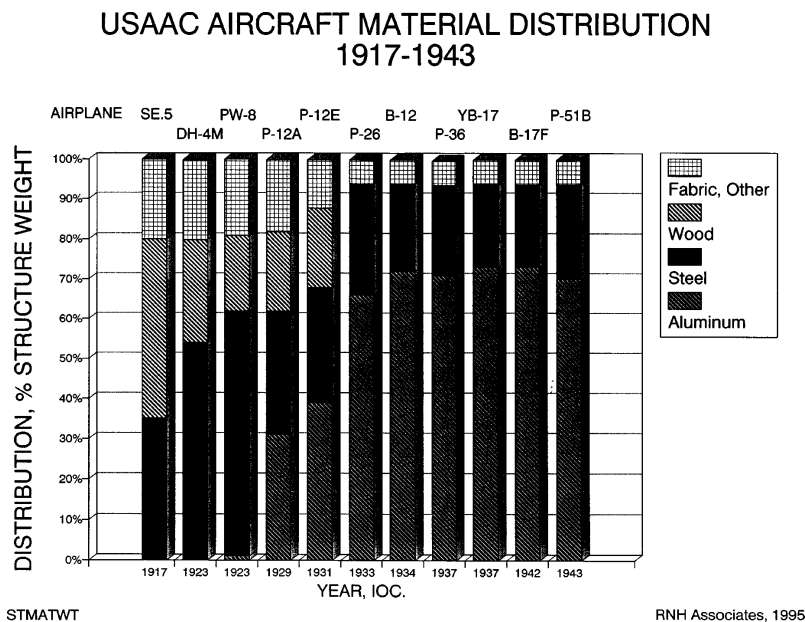


Figure 3.3 Specific Tensile Strength as a Function of Test Temperature (100 hours exposure at test temperature)

The distributions of materials in pre- and post-World War II aircraft are shown in Figures 3.4 and 3.5, respectively. The replacement of wood by aluminum in the prewar aircraft extending over a decade from 1923 to 1933 is clearly illustrated in Figure 3.4, as is the fact that the penetration of aluminum alloys into aircraft structures was essentially complete by 1933. With



*Figure 3.4 USAAC Aircraft Material Distribution 1917-1943*

a few exceptions, the SR-71 and F-22, aluminum alloys have accounted for about 70 percent of the structural weight of aircraft from 1934 to the present day. The exceptions are important because they are examples of systems in which performance demands drove the choice of exotic materials (titanium in the case of the SR-71 and titanium and composites in the case of the F-22), despite the high cost.

The influence of performance on the choice of materials is better illustrated by a plot of the distribution of materials, as a function of maximum airspeed, as shown in Figure 3.6. One should note the rapid decline in the use of aluminum and the introduction of titanium in U.S. fighters, attack aircraft, and trainers as the maximum Mach number exceeds 2.4, due to the rapid increase in structural temperatures with increasing airspeed (Figure 3.7). The same trend holds true for bombers and transport aircraft (Figure 3.8).

Much has been said and written about the use of polymer matrix composites as structural materials in modern high-performance aircraft, but it is worth examining the record to ascertain how extensively these materials are actually used. Data on this issue for fighter and attack aircraft and for transports, are summarized in Figures 3.9 and 3.10, respectively. As far as fighter and attack aircraft are concerned, the composite fraction of the structural weight has not changed significantly since the early 1980s. Even composite aircraft, such as the AV-8B, Rafale, B-2A, and the F-22A, incorporate only about 30 percent of their structural weight as

## USAF AIRCRAFT MATERIAL DISTRIBUTION FIGHTERS, ATTACK & TRAINERS, 1955-1996

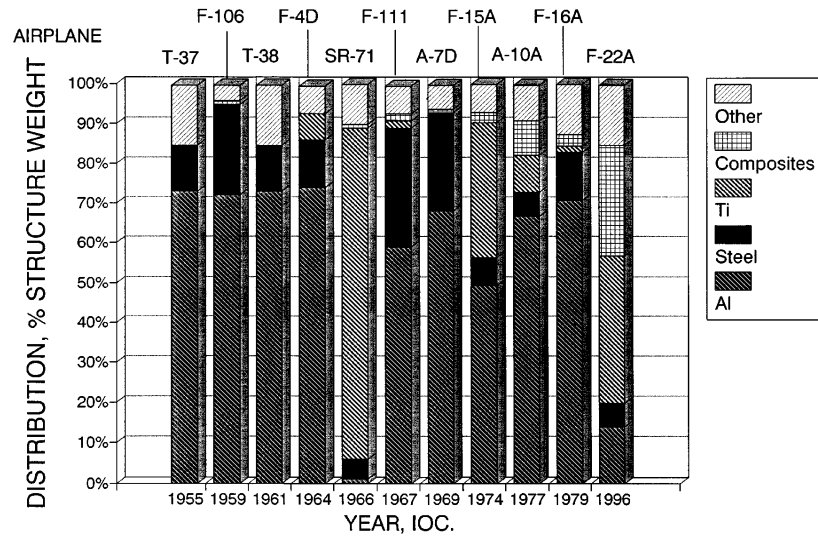


Figure 3.5 USAF Aircraft Material Distribution vs. Year, IOC (Fighters, Attack & Trainers, 1955-1996)

## USAF AIRCRAFT MATERIAL DISTRIBUTION FIGHTERS, ATTACK & TRAINERS, 1955-1996

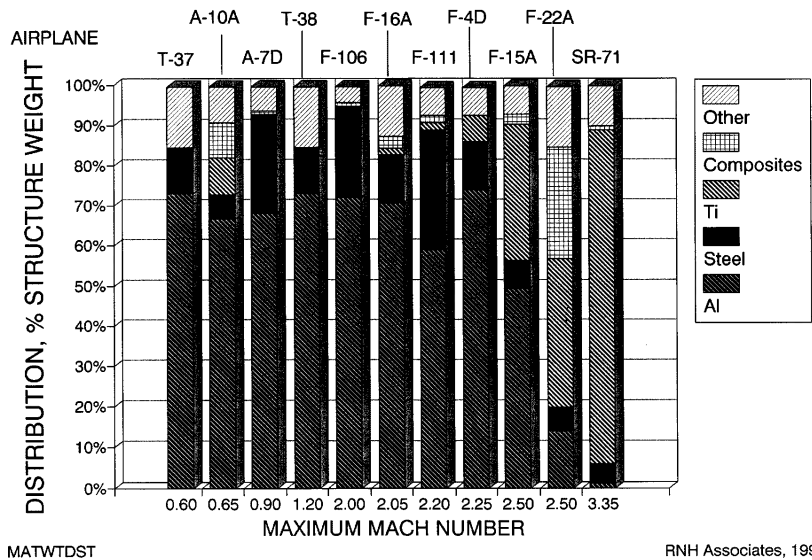
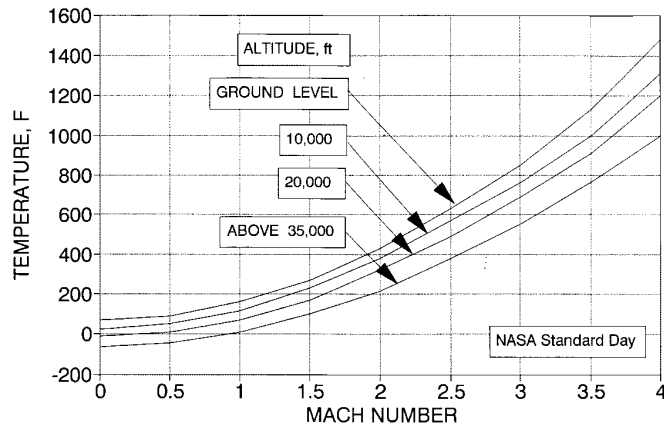


Figure 3.6 USAF Aircraft Material Distribution vs. Maximum Mach Number

## AIRCRAFT STRUCTURAL TEMPERATURES ADIABATIC WALL TEMP, F.



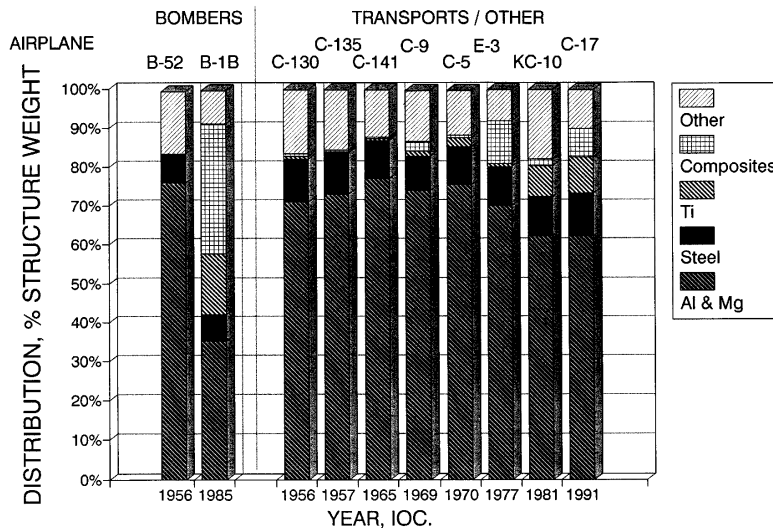
STRCTEMP

RNH Associates, 1995

*Figure 3.7 Aircraft Material Structural Temperatures vs. Mach Number*

polymer matrix composites. Of course, because of the lower densities of the composites, compared with steel, titanium, and aluminum, the volume fraction of the airframe that is composite is considerably greater and may exceed 60 percent in some cases. It is important to note that in the case of the systems shown in Figure 3.9, the driver for the use of composites is performance

## USAF AIRCRAFT MATERIAL DISTRIBUTION BOMBERS & TRANSPORTS, 1956-1991



MATWTDST

RNH Associates, 1995

*Figure 3.8 USAF Aircraft Material Distribution vs. Year, IOC (Bombers & Transports 1956-1996) Maximum Mach*



### COMPOSITE STRUCTURE: COMBAT AIRCRAFT ADVANCED COMPOSITES, % STRUCTURE WEIGHT

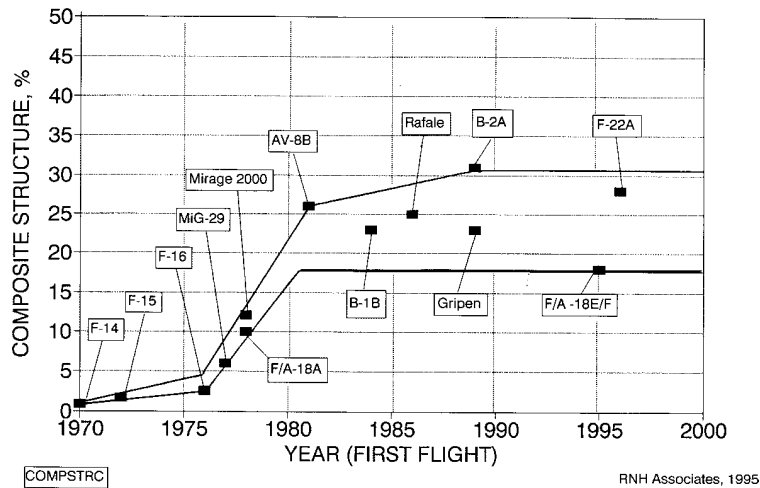


Figure 3.9 Composite Structure: Combat Aircraft (Advanced Composites, % Structure Weight)

in the form of weight, ability, useful payload, and speed. In the case of transport aircraft, where cost and reliability are the predominant factors, composites account for no more than 20 weight percent of the structure, and even then they have been used more extensively in European than in U.S. aircraft,, as shown in Figure 3.10.

### COMPOSITE STRUCTURE: TRANSPORT AIRCRAFT ADVANCED COMPOSITES, % STRUCTURE WEIGHT

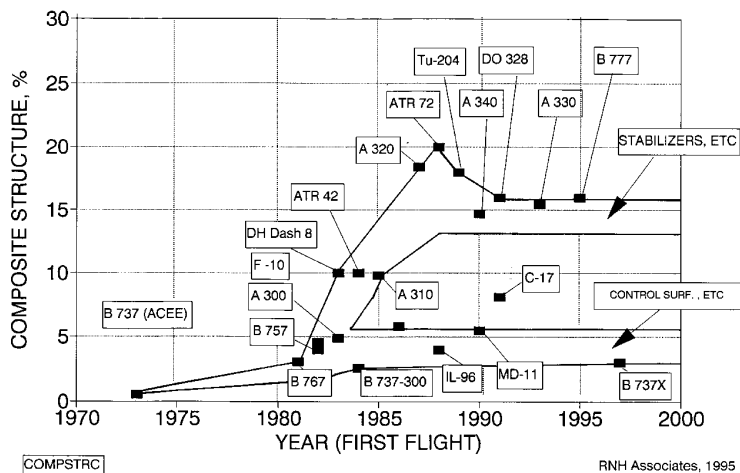
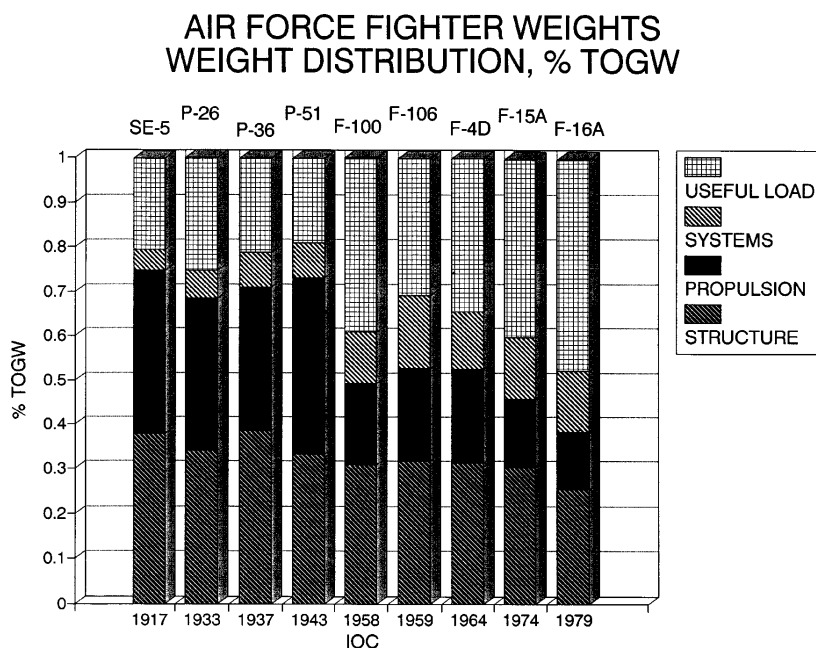


Figure 3.10 Composite Structure: Transport Aircraft (Advanced Composites, % Structure Weight)

A critical performance parameter for any aircraft is the fraction of the takeoff gross weight (TOGW) that is useful load. The trend of this parameter for fighter aircraft from 1917 to 1979 is given in Figure 3.11, showing that the fraction of the TOGW that is useful load has doubled over this period. Interestingly, this gain has not been due to savings in the structural weight or the weights of various systems avionics, but rather has been achieved because of dramatic improvements in the performance of propulsion systems. The most dramatic improvement in the latter occurred upon the introduction of the jet engine (see P-51 vs. F-100), illustrating that system changes can have as dramatic an effect on performance as materials changes.

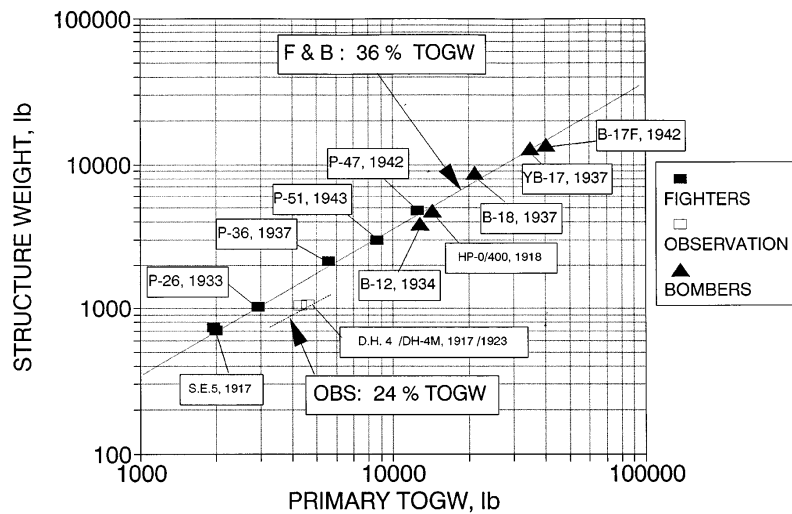


FTRWTS

Figure 3.11 Air Force Fighter Weights (Weight Distribution, % TOGW)

An interesting observation is that new materials have historically had relatively little effect on the relationship between structure weight and TOGW. This is clear from Figure 3.12, which shows that prewar aircraft follow the same correlation, regardless of whether they were manufactured primarily from wood or aluminum, and from Figure 3.13, which shows postwar aircraft that used a much wider range of materials. A comparison of these correlations shows that a significant improvement in the payload characteristics occurred between 1943 and 1955. This timeframe does not coincide with the introduction of any new structural material or new structure type, but it does coincide with the introduction of higher power-to-weight propulsion systems in the form of jet engines, which, of course, also employ new materials. Note, however, that the advantage of turbine power plants, as far as the relationship between structural weight and TOGW is concerned, becomes smaller as the takeoff gross weight increases. Finally, it is important to emphasize that the use of advanced materials has had a dramatic influence on other performance parameters, such as the maximum Mach number and observability, as previously noted.

### MILITARY AIRCRAFT STRUCTURAL WEIGHTS 1917-1943

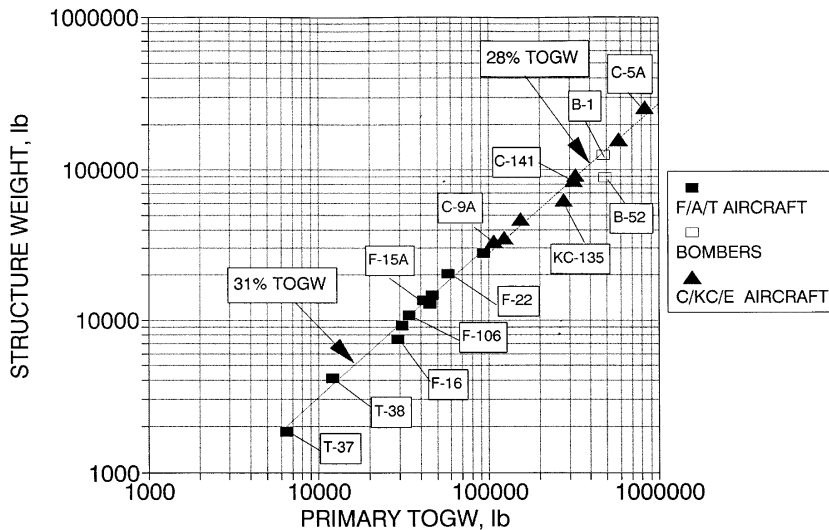


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Figure 3.12 Military Aircraft Structural Weights 1917-1943

### MILITARY AIRCRAFT STRUCTURAL WEIGHTS 1955-1996



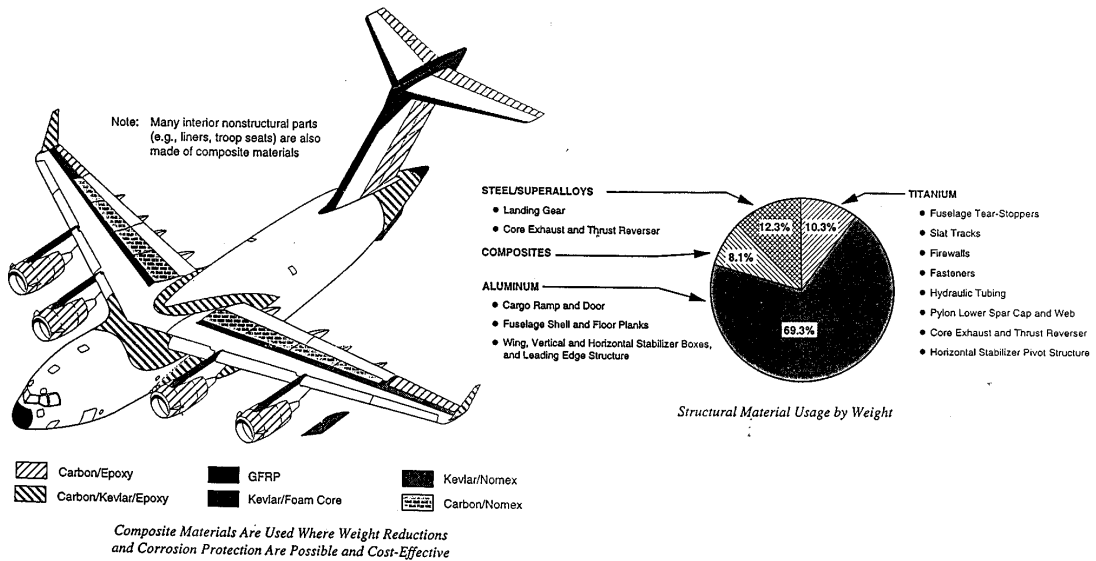
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RNH Associates, 1995

Figure 3.13 Military Aircraft Structural Weights 1955-1996

Just where are various materials being used in current aircraft? Because each aircraft is unique, it is impossible to generalize, but reference to a specific example illustrates the trends.

## C-17A STRUCTURAL MATERIAL USAGE



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Figure 3.14 C-17A Structural Material Usage

## USAF AIRCRAFT DEVELOPMENT CYCLES

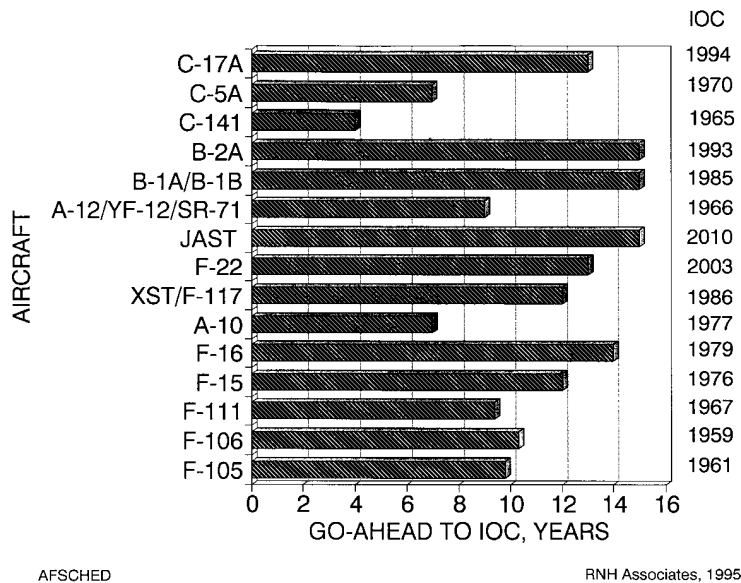


Figure 3.15 USAF Aircraft Development Cycles

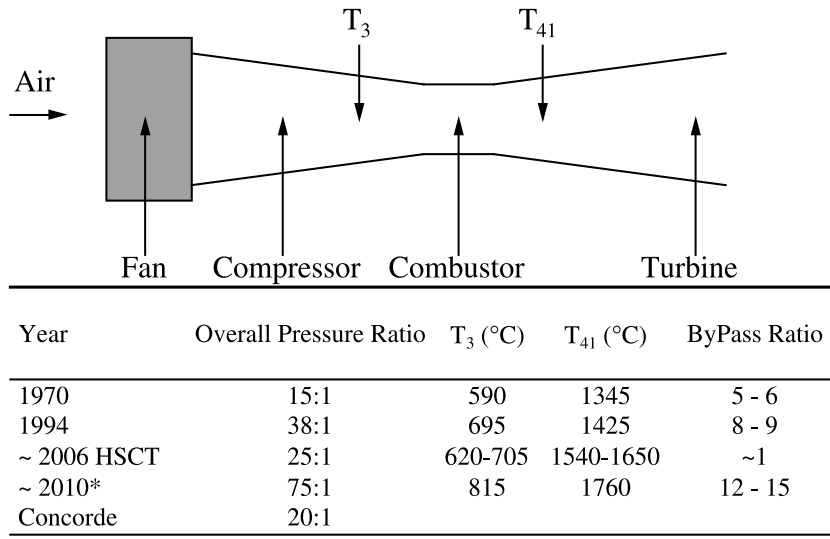
The case that we have chosen is the C-17A, the Air Force's new heavy-lift transport. As shown in Figure 3.14, almost 70 percent of the structural weight of this aircraft is aluminum alloys, with the "advanced" materials in the form of composites and titanium accounting for only eight percent and ten percent, respectively. In general, new materials are introduced in noncritical components, or into components of high redundancy (e.g., engine cowlings, winglets, tail cones, and radomes), partly to gain manufacturing experience and partly to accumulate flight hours. However, this implies that the time required to introduce a new structural material into aircraft is governed, to a large extent, by the development cycle, which is currently between 10 and 15 years (see Figure 3.15). Assuming that several generations of aircraft are required to introduce a new structural material, it is not difficult to see that many decades may pass between the first manufacture of a material and its extensive use in an airframe.

The final issue we wish to discuss is cost, because no relevant analysis can be conducted without considering this factor. The dramatic increase in the cost of military aircraft, particularly after WW II, is evident by the fact that the F-22 costs an order of magnitude more per pound than did an F-86. Conversely, the per-pound cost of civil transport aircraft has risen only modestly by a factor of two over the same period. It is difficult to attribute this difference to the introduction of advanced structural materials, because the composite content of a modern airliner is not commensurably different from that of a modern military aircraft (see Figures 3.9 and 3.10). A more likely explanation for the cost discrepancy lies in procurement procedures, specifications, and in the much more sophisticated avionics that are characteristic of military systems.

### **3.3 Propulsion Systems**

The second major system in an aircraft is the propulsion system. Prior to the mid-1940s, propulsion was due exclusively to the internal combustion engine (ICE). ICEs developed dramatically in the period from 1935 to 1945, but by the end of WW II, ICEs had achieved a maximum power-to-weight ratio at a great cost in increased complexity. At that point (1938-1940), a revolution occurred with the development of the turbojet more or less simultaneously in England and Germany. Not only was the turbojet a much simpler device, but it offered dramatic improvements in the power-to-weight ratio (commonly expressed as thrust-to-weight ratio). Since these early times, the performance of the turbojet and its derivatives, turbofans and turboprops, has improved dramatically, and much of this improvement can be attributed to better materials. The driver for advanced materials in propulsion systems has been higher thermodynamic efficiency, which translates into higher combustion temperatures, lower specific fuel consumption, and reduced weight. The evolution in engine operating parameters is summarized in Figure 3.16 together with projections into the future.

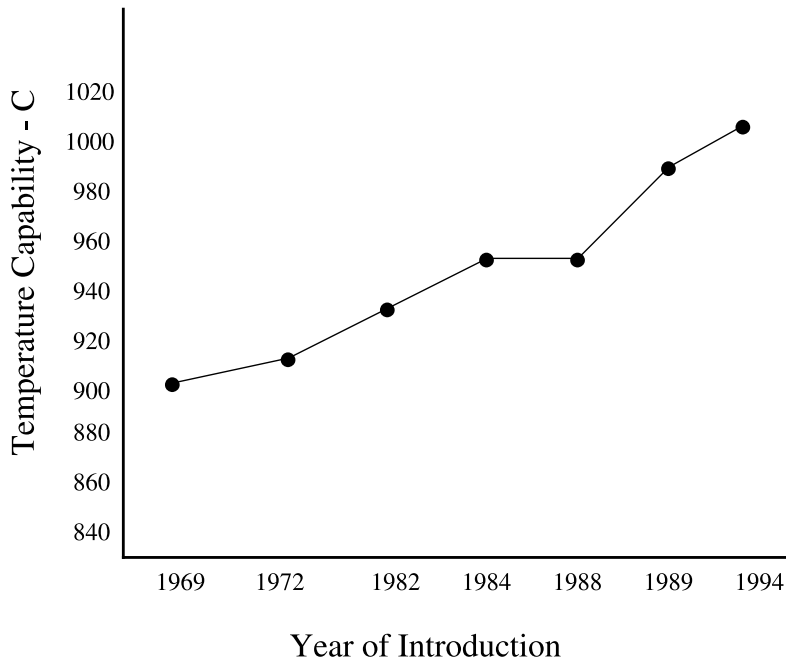
Of particular importance has been the evolution in the turbine blade alloy temperature capability, as shown in Figure 3.17. However, the development of better alloys, particularly nickel-based superalloys, is only part of the story because the most dramatic improvements can be attributed to materials processing and component design. In the case of turbine blades, it was the introduction of monolithic single-crystal structures with internal air cooling that led to the great increases in efficiency. Reductions in weight have been achieved by using lightweight/



\* Cannot make this engine due to materials limitations

*Figure 3.16 Time Series of Engine Operating Parameters*

high-stiffness materials for compressor blades. The introduction of graphite/polymer composites into the RB-211 is perhaps a lesson in the dangers of introducing a new material into an engine when sufficient flexibility in cost and delivery schedules is not available. Nevertheless,



*Figure 3.17 Turbine Blade Alloy Temperature Capability*

new materials will continue to be introduced into engine systems with lightweight/high-stiffness materials, such as the intermetallics and metal-matrix composites, leading the way. The introduction of these materials, together with evolution in design (e.g., in the use of a single fluid for lubrication and propulsion), offers continued and dramatic improvements in engine performance.

### **3.4 Fuels and Lubricants**

There are perhaps few Air Force materials that have changed as little over the past 40 years as fuels. The standard fuels, ranging from JP-4 through JP-8 and derivatives thereof, are basically refined hydrocarbons of the kerosene type. They lead to coking, are susceptible to combustion instabilities, and have a minimal potential for cooling. Likewise, current lubricants can be traced back several decades and, again, are hydrocarbon derivatives of synthetic esters and fluorinated ethers. While considerable development has occurred in lubricants, the current philosophy is to modify the properties of contact interfaces. This philosophy would be abandoned upon the introduction of magnetic bearings.

Dramatic developments are now occurring in fuels and lubricant technology, and these developments are discussed at great length later in this report. Briefly, the development of high-heat-sink fuels, endothermic fuels, and chemically reacting fuels offers great advances in propulsion technology and should result in greatly reduced fouling, maintenance, emissions, and signature, as well as increased component lifetime. The concept of a single fluid for lubrication and propulsion would also have a major favorable impact on Air Force operations, and this technology is now in the research stage.

With regard to missiles and rockets, little has changed in propellant fuel and oxidizer technology over the past three decades, except for the more extensive use of liquid hydrogen as a fuel. Our solid propellants are still based on ammonium perchlorate as the oxidizer and aluminum-filled hydrocarbon polymers (e.g., polybutadiene) as the fuel. The need for higher specific impulse propellants is well recognized, not only for improving performance, but also for reducing cost, but introduction of new technologies has been slow. As a case in point, we note that the superoxidizer, ammonium dinitramide, has been fielded by the Russians in several missile systems, but has yet to be incorporated into any U.S. missiles or launch vehicles. Part of the problem is a reluctance on the part of system designers to depart from time-proven technologies, even if significant increases in performance can be achieved. Equally important is the poor prospect that new propulsion systems will be sponsored and fielded by the military in the future.

Gas turbine engine lubricants currently used by the Air Force are based on polyesters that are capable of operating to 400°F. Other important fluids include polyalphaolefin-based hydraulic fluids and dielectric coolants. Both liquids and solids are utilized in space lubrication, coatings are utilized in several applications, and greases are used in some expendable engines. There is also current interest in biodegradable hydraulic fluids, and the technology is presently available for aerospace nonflammable hydraulic fluids.

### **3.5 Vision Protection**

The development and proliferation of laser technology in the 1980s and early 1990s pose a serious threat to low-flying aircraft, in that ground-based lasers can be used to a the pilot. For

instance, it has been demonstrated that a shoulder-fired laser aimed with a telescopic sight can incapacitate a pilot of an F-4 undergoing evasive maneuvers at a distance of 14 km. Because of the rapidly developing power capabilities of lasers brought about by advances in nonlinear optical materials technology, it is not difficult to envisage the seriousness of this threat to current and future Air Force operations. As of 1995, the only currently available protection against this threat are dye systems (goggles), which are effective against three wavelengths during daytime missions only. Development of more effective protection systems is an area of active research, and many new concepts are currently being explored.

### **3.6 Pyrotechnics**

The principal line of defense for Air Force pilots against heat-seeking missiles is flares, which are ejected from the aircraft when a threat is perceived or detected. Current flares are magnesium-based systems that are tailored to simulate the emissions from a jet engine. This technology has been effective against first and second generation seeker systems, but seekers are now being developed, or have been fielded, that lock on to emissions at wavelengths outside the flare spectrum, or that can distinguish between the trajectory of a flare and an aircraft.